METHOD OF FORMING INTERLAYER CONNECTIONS IN INTEGRATED OPTICAL CIRCUITS, AND DEVICES FORMED USING SAME

TECHNICAL FIELD

[1] The present invention relates generally to integrated photonic or optical circuits, and more specifically to forming interlayer connections in such circuits.

BACKGROUND OF THE INVENTION

[2] Optical or photonic devices are becoming increasingly prevalent in many areas of technology today. For example, many communications systems include fiber optic cables and associated optical components for transmitting and receiving optical signals over the cables. Such optical systems provide very high data transfer rates and thus allow large amounts of data to be transferred very quickly, as will be appreciated by those skilled in the art.

[3] In modern optical systems, optical components are integrated on a single substrate to thereby form compact, multifunctional, optical integrated circuits. These optical integrated circuits are analogous to electronic integrated circuits in which electronic components are formed and interconnected on a substrate to perform a desired function. In electronic integrated circuits, multiple layers are formed on the substrate and electronic components and required interconnections among such components are formed in these layers. The use of multiple layers allows more components to be formed on a single substrate, and also allows for easier and more efficient interconnection of such components.

[4] Ideally, optical integrated circuits would also utilize multiple layers for the same reasons as electronic integrated circuits, namely to allow the formation of more optical components and easier and more efficient interconnection of the optical components. With optical integrated circuits, however, a unique problem is encountered that is different than electronic integrated circuits. When multiple layers are used, each layer must at selected points be coupled to one or more of the other layers to properly interconnect all the components formed in the layers.

This is accomplished in a simple manner in electronic integrated circuits, as illustrated in **FIG. 1** which shows a cross-sectional view of a portion of a conventional electronic integrated circuit ***100*** in which a via or electrical interconnect ***102*** electrically couples a first layer ***104*** to a second layer ***106*** formed on a substrate ***108***. In an electronic integrated circuit, the interconnect ***102*** is simply formed where required to interconnect the layers ***104*** and ***106***, which are conductive layers, and electrons flow between these layers through the interconnect.

[5] In optical integrated circuits, waveguides are used in place of conductive layers and transfer optical energy or light between optical components. Unlike the electrons flowing in an electronic integrated circuit, light propagating through a layer cannot simply make a 90 degree turn and then propagate through an adjacent layer. For example, if the layers ***102-106*** in **FIG. 1** correspond to waveguide layers in an optical integrated circuit, then light propagating through the layer ***104*** will not make a 90 degree turn and thereafter propagate through the interconnect ***102*** and into the layer ***106***. In fact, light propagating through the layer ***104*** would be confined to this layer and would not enter the interconnect ***102*** at all, as will be appreciated by those skilled in the art.

[6] As a result of the problems associated with interconnecting multiple layers in optical integrated circuits, currently such circuits are limited to a single layer. This increases the cost and size of the circuits while limiting their functionality. The formation of "micro mirrors" to direct light from one layer to another has been proposed, but such an approach complicates the manufacture of the optical integrated circuit, which affects the cost and reliability of the circuit.

[7] There is a need in optical integrated circuits to interconnect multiple layers so that light can propagate from one layer to another and thereby allow multilayer optical integrated circuits to be formed.

SUMMARY OF THE INVENTION

[8] According to one aspect of the present invention, a method of optically interconnecting layers in an optical integrated circuit having a substrate includes forming a first optical transmission layer over the substrate. A first cladding layer is formed on the first optical transmission layer and portions of the first cladding layer removed to form an angled sidewall in the first cladding layer. An optical interconnect layer is then formed on the angled sidewall of the first cladding layer and on an exposed portion of the first optical transmission layer.

BRIEF DESCRIPTION OF THE DRAWINGS

[9] **FIG. 1** is a cross-sectional view of a portion of a conventional electronic integrated circuit showing a via or electrical interconnection that electrically couples one layer to another in the integrated circuit.

[10] **FIGS. 2A-2F** are cross-sectional views illustrating the formation of an optical interconnect according to one embodiment of the present invention.

[11] **FIGS. 2G-I** are cross-sectional views and **FIGS. 2J-K** are top views illustrating the formation of an optical interconnect according to another embodiment of the present invention.

[12] **FIG. 3** is a functional block diagram illustrating an optical integrated circuit including optical interconnects as shown in **FIGS. 2F** and/or **2I** contained in an electronic or photonic system according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[13] **FIGS. 2A-F** are cross-sectional views illustrating the formation of an optical interconnect (see **FIG. 2F**) for a multilayer optical integrated circuit ***200*** according to one embodiment of the present invention. The formation of the optical interconnect through the process illustrated in these figures may be done using conventional deposition, photolithography, etching, and chemical mechanical

planarization (CMP) techniques. As a result, multilayer optical integrated circuits ***200*** may be fabricated in a cost effective and reliable manner, as will be explained in more detail below.

[14] In the following description, certain details are set forth in conjunction with the described embodiments of the present invention to provide a sufficient understanding of the invention. One skilled in the art will appreciate, however, that the invention may be practiced without these particular details. Furthermore, one skilled in the art will appreciate that the example embodiments described below do not limit the scope of the present invention, and will also understand that various modifications, equivalents, and combinations of the disclosed embodiments are within the scope of the present invention. Finally, the operation of well known operations has not been shown or described in detail below to avoid unnecessarily obscuring the present invention.

[15] **FIG. 2A** illustrates the optical integrated circuit ***200*** including a substrate ***201*** on which a suitable lower dielectric layer ***202*** is formed. The substrate ***201*** may be silicon or other suitable material, and the lower dielectric layer ***202*** may be a layer of silicon dioxide SiO_2 formed on the silicon substrate. An optical transmission layer ***204*** is formed on the lower dielectric layer ***202*** from any dielectric material suitable for the transmission of light, such as silicon oxynitride SiON. The optical transmission layer ***204*** corresponds to a first "active" layer of the optical integrated circuit ***200***, and initially the layer is processed to form desired optical components in the layer, including active devices and waveguide interconnecting such devices.

[16] **FIG. 2B** illustrates an example of the optical transmission layer ***204*** after processing, with the layer now including three separate layers ***204a-c***. A first dielectric layer ***206*** formed from a suitable dielectric material, such as silicon dioxide SiO_2, is then formed on the optical transmission layers ***204a-c***. A variety of suitable dielectric materials may be utilized for the layer ***206***, and the layer may be formed through a variety of different techniques, such as being deposited through a

suitable high-density plasma process so that the layer completely fills openings between the optical transmission layers ***204a-c*** as shown in **FIG. 2B**.

[17] Referring now to **FIG. 2C**, the deposited dielectric layer ***206*** is then chemically mechanically polished to remove portions of the layer above the optical transmission layers ***204a-c*** and to planarize the optical transmission layers and the remaining portions of the dielectric layer between the optical transmission layers. A first cladding layer ***208*** formed from a suitable dielectric material, such as silicon dioxide SiO_2, is formed on the optical transmission layers ***204a-c*** and remaining portions of the dielectric layer ***206*** as shown in **FIG. 2D**. The first cladding layer ***208*** will have a substantially planar surface since the layers ***206***, ***204a-c*** on which the cladding layer is formed were planarized in the previous step of the process. A variety of suitable dielectric materials may be utilized for the first cladding layer ***208*** so long as an index of refraction n_1 of the optical transmission layers ***204a-c*** is greater than an index of refraction n_2 of the cladding layer, as will be understood by those skilled in the art. The first dielectric layer ***206*** also has an index of refraction that is different than the index of refraction n_1 of the optical transmission layers ***204a-c***, and would typically be the same as the index of refraction n_2 of the first cladding layer ***208***.

[18] **FIG. 2E** illustrates mesa structures ***210*** which are then formed on the first cladding layer ***208*** at desired locations above the optical transmission layers ***204a-c***. The mesa structures ***210*** are so named because of the physical shape of the structures, with each mesa structure having an angled sidewall ***212*** and a planar upper portion ***214***. The mesa structures ***210*** are positioned above the optical transmission layers ***204a-c*** so that a base ***216*** of the angled sidewall ***212*** overlaps a one of the optical transmission layers ***204a-c*** to which an optical interconnect is to be coupled. In the example of **FIG. 2E**, the optical transmission layer ***204a*** is the layer to which an optical interconnect will be coupled, will be described in more detail below. The optical transmission layers ***204b,c*** would be coupled to optical

interconnects in the same way as optical transmission layer ***204a***, and thus will not be described in more detail below.

[19] To form the mesa structures ***210***, regions of photoresist (not shown) are patterned on the first cladding layer ***208*** where the mesa structures are to be located. These photoresist regions initially have substantially vertical sidewalls and are then reflowed to form the mesa structures ***210*** having the angled sidewalls ***212***. In other words, the photoresist regions are formed and then heated, causing the regions to melt slightly and thereby form the mesa structures ***210***. The photoresist regions can be formed slightly out of focus to adjust the angle of the resulting sidewalls ***212*** formed during reflow of the regions. In one embodiment, the photoresist regions are reflowed at a temperature between 140° C and 160° C. The angled sidewalls ***212*** of the mesa structure ***210*** must have a required angle θ, where θ is the angle defined between the sidewall ***212*** and the upper surface of the first cladding layer ***208*** as shown in **FIG. 2E**. The required value for the angle θ will be discussed in more detail below.

[20] Referring now to **FIG. 2F**, the mesa structure ***210*** and exposed portions of the first cladding layer ***208*** are then removed, such as through a dry etch process, at the same rate to form an angled sidewall ***218*** in the first cladding layer ***208*** and expose the lower optical transmission layer ***204a***. By removing the mesa structure ***210*** and exposed portions of the first cladding layer ***208*** at the same rate, the angled sidewall ***218*** in the first cladding layer ***208*** has approximately the same angle θ as the sidewall ***212*** of the mesa structure. A second optical transmission layer ***220*** is then formed on the lower optical transmission layer ***204a*** and on the first cladding layer ***208*** including the angled sidewall ***218***. The second optical transmission layer ***220*** is formed from a suitable dielectric material having the same index of refraction as the lower optical transmission layer ***204a***. Thus, when the lower optical transmission layer ***204a*** is silicon oxynitride SiON, the second optical transmission layer ***220*** will also be a silicon oxynitride layer having the same index of refraction. The first and second optical layers ***204a***, ***220*** have the same

index of refraction so that the layers collectively form a waveguide, with light having a wavelength λ propagating through both layers from right to left as indicated by an arrow ***226*** in the example of **FIG. 2E**.

[21] An angled portion of the second optical transmission layer ***220*** forms a vertical optical interconnect ***222*** that couples the lower optical transmission layer ***204a*** to an upper optical transmission layer ***224***. Thus, at this point a multilayer optical integrated circuit ***200*** has been formed, with optical components (not shown) coupled to the lower optical transmission layer ***204a*** being coupled through the vertical optical interconnect ***222*** to the upper optical transmission layer ***224*** and optical components (not shown) coupled to the upper optical transmission layer. The optical components coupled to the upper optical transmission layer ***224*** would typically be formed during formation of the second optical transmission layer ***220***.

[22] In operation, light having the wavelength λ propagates through the layers ***204a***, ***220*** and then through the vertical optical interconnect ***222*** and into the layer ***224***, as illustrated by a dotted line arrow ***228*** in **FIG. 2F**. The light is confined to the optical interconnect ***222*** through total internal reflection so long as the angle θ of the optical interconnect is less than a specified angle. This ensures light propagating through the layers ***204a***, ***220*** will enter the vertical optical interconnect ***222*** at an angle that is less than a critical angle to ensure total internal reflection within the optical interconnect, as will be understood by those skilled in the art. Moreover, the angle θ also ensures the light is confined through total internal reflection when propagating from the vertical optical interconnect ***222*** into the upper optical transmission layer ***224***, as will also be appreciated by those skilled in the art. In one embodiment, where the layers ***204a***, ***220*** are silicon oxynitride SiON and the cladding layer ***208*** is silicon dioxide SiO_2, the angle θ of the optical interconnect must be less than 50 degrees.

[23] **FIGS. 2G-2K** are cross-sectional views illustrating the formation of an optical interconnect according to another embodiment of the present invention. In this embodiment, instead of forming optical components in the upper optical

transmission layer ***224*** during formation of this layer, a second cladding layer ***230*** is formed on the second optical transmission layer ***220*** as shown in **FIG. 2G**. The second cladding layer ***230*** is also formed from a suitable dielectric material, such as silicon dioxide SiO_2, having the same index of refraction as the first cladding layer ***208***.

[24] After formation of the second cladding layer ***230***, a non-selective chemical mechanical planarization process is performed, with the process removing the second cladding layer ***230*** at the same rate as the second optical transmission layer ***220***. **FIG. 2H** illustrates the integrated circuit ***200*** after the non-selective chemical mechanical planarization process has been completed. Because the process removes the second cladding layer ***230*** and second optical transmission layer ***220*** at the same rate, the upper surface of the integrated circuit ***200*** is planarized, with only the lower portions of the second optical transmission layer under the second cladding layer and the angled sidewall portions of the second optical transmission layer remaining. Notice that in **FIG. 2H**, an optical interconnect coupled to the lower optical transmission layer ***204c*** is shown in addition to an optical interconnect coupled to the lower optical transmission layer ***204a***.

[25] At this point, an upper optical transmission layer ***232*** is formed on the planarized surface from a suitable dielectric material, such as silicon oxynitride SiON, as shown in **FIG. 2I**. The material used for the upper optical transmission layer ***232*** is determined by the materials used for the optical transmission layers ***204***, ***220***, with the upper optical transmission layer being formed from the same material and having the same index of refraction as the layers ***204***, ***220***. In this way, the waveguide collectively formed by the layers ***204a***, ***220*** is coupled through a vertical optical interconnect ***234*** to the upper optical transmission layer ***232***. In operation, light having a wavelength λ propagates through the layers ***204a***, ***220*** from right to left in **FIG. 2I** and then through the corresponding vertical optical interconnect ***234*** and into the layer ***232***. Similarly, light having a wavelength λ

propagates through the layers ***204c***, ***220*** from left to right and then through the corresponding vertical optical interconnect ***234*** and into the layer ***232***.

[26] Although from **FIG. 2I** it appears that the upper optical transmission layer ***232*** couples together the waveguide formed by layers ***204c***, ***220*** on the left to the waveguide formed by the layers ***204a***, ***220*** on the right, each waveguide is actually coupled to separate segments of the upper optical transmission layer as shown in **FIGS. 2J** and **2K**. **FIG. 2J** is a top view illustrating the coupling of the left waveguide including layers ***204c***, ***220*** through the corresponding vertical optical interconnect ***234*** to a first segment of the upper optical transmission layer ***232***. Similarly, **FIG. 2K** is a top view illustrating the coupling of the right waveguide including layers ***204a***, ***220*** through the corresponding vertical optical interconnect ***234*** to a separate segment of the upper optical transmission layer ***232***. The layers ***220*** in **FIGS. 2J** and **2K** are shown with dotted lines since these layers are on a lower layer of the integrated circuit ***200*** in the top views depicted in these figures. When the upper optical transmission layer ***232*** is formed, the layer is patterned as required to make connections to the required underlying vertical optical interconnects ***234***. The process illustrated in **FIGS. 2A-2I** may be repeated to form additional layers in the optical integrated circuit 200 over the upper optical transmission layer ***232***, as will be appreciated by those skilled in the art.

[27] In one embodiment, the substrate is silicon, optical transmission layers ***204***, ***220***, and ***232*** are silicon oxynitride SiON, and layers ***206***, ***208*** and ***230*** are silicon dioxide SiO_2. In another embodiment, the thickness of the layer ***206*** is approximately 10,000 angstroms, layer ***208*** is approximately 5,000 angstroms, layer ***230*** is approximately 8,000 angstroms, and lower dielectric layer ***202*** is approximately 30,000 angstroms.

[28] **FIG. 3** is a block diagram of an electronic or optical system ***300*** including system circuitry ***302*** containing an optical integrated circuit ***304*** including the optical interconnects ***222*** of **FIG. 2F** and/or the optical interconnects ***234*** of **FIG. 2I**. The system circuitry ***302*** includes circuitry for performing required functions, such as

communicating data over an optical network (not shown) using the optical integrated circuit ***304***. One or more input devices ***306***, such as a keyboard, may also be included in the system ***300*** to allow a user to input data. The system ***300*** may also include one or more output devices ***308***, such as a video display, to provide data to the user.

[29] Even though various embodiments and advantages of the present invention have been set forth in the foregoing description, the above disclosure is illustrative only, and changes may be made in detail and yet remain within the broad principles of the present invention. Therefore, the present invention is to be limited only by the appended claims.